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TECHNICAL MEMORANDUMS  
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 202.

WIND TUNNEL OF ZEPPELIN AIRSHIP COMPANY.

By Max M. Munk.

From Zeitschrift für Flugtechnik und Motorluftschiffahrt,  
January 31, and February 15, 1921.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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WIND TUNNEL OF ZEPPELIN AIRSHIP COMPANY.\*

By Max M. Munk.

At the Zeppelin Airship Yard in Friedrichshafen there has just been completed the largest and most modern aerodynamic laboratory in existence. The writer wishes to improve the opportunity, in connection with the description of this laboratory, designed by himself, to discuss the general considerations for the designing of such laboratories.

The essential feature of such a plant is an artificially produced air stream, uniform for some considerable length and diameter. To this air stream parts of aircraft and small models are exposed. These parts and models are connected with balances (located outside the air stream), which measure the forces exerted upon them by the air stream. From the data thus obtained, conclusions are drawn regarding the construction of aircraft. The air stream is also used for experiments with radiators, propellers and windmills, for testing instruments and steering devices, and for determining the pressure distribution on bodies exposed to it, such as models of buildings, for example.

Fig. 1 is the ground plan of the Zeppelin wind tunnel, showing the essential parts of such a plant. The air is driven by a propeller into the side channels, then flows through the "honey-

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\*From Zeitschrift für Flugtechnik und Motorluftschiffahrt, January 31, 1921, pp. 20-22 and Feb. 15, 1921, pp. 35-38.

comb," a sieve-like device, into a comparatively large space from which it passes through a converging cone into the experiment chamber. Here it flows past the object of the experiment and is drawn into the exit cone and conducted back to the propeller. The latter is driven by an engine situated in the wedge-shaped space which divides the return flow.

Fig. 2, a cross-section, shows a small room over the experiment chamber. Here are the balances, the device for regulating the power plant, the airspeed indicator and the other more delicate instruments. On either side of the open air stream, in the larger space below, are the coarser devices. The remaining space, especially between the exit cone and the return conduits, is utilized for store-rooms.

Principal Dimensions.- The size of the wind tunnel is determined by the dimensions of the open portion of the air stream and its maximum velocity. Its cross-section is usually circular or polygonal, so that it is possible to speak of its diameter without being misunderstood. The length of the open portion lies ordinarily between its diameter and twice the same. In longer experiment chambers, it is difficult to maintain a uniform velocity. Greater lengths would not avail much, since, with correspondingly long models, the airflow would be affected by the relatively too small diameter of the air stream. According to Reynolds law, the effective size of the tunnel depends on the product of the velocity and a determining factor, equal to about the diameter of the useful portion of the air stream. This law is applicable,

however, only within certain limits. If the size of the tunnel is continually reduced and the velocity correspondingly increased, the building can be made smaller and cheaper, but the required power, and hence the power plant, is larger and more expensive. We would thus obtain a very small diameter and a very high velocity, which would no longer be small in comparison with the velocity of sound in the air (about 1100 feet per second). Then, however, the airflow would differ noticeably from that at normal flight speed and consequently prohibit experiments at such high velocities. Long before this point could be reached, however, other objections would arise against excessive wind velocities. For an equal magnitude of the product of the length of the model and the velocity, the air forces, measured absolutely, remain the same. Hence, the size of the wires, or other means of holding the model in place, would necessarily remain the same and would accordingly exert an increasing influence on the airflow about the model, in proportion as the relative size of the latter is diminished, and finally the whole picture of flow about the model would become essentially distorted. In fact, the greater the velocity, the greater would be the relative strength of the air forces, so that the supports would need to be made still stronger. Moreover, the smaller the model, the less accurately it can be made. For all these reasons, with a given product of the diameter of the experiment chamber and the velocity of the airflow, the larger tunnel should generally be given the preference. For testing instruments, it is desirable that the velocity should not

fall much below 30 meters (98 ft) per second. In the Zeppelin plant, the open portion of the air stream has a diameter of 3 m. (9.8 ft) and the maximum velocity is about 50 m. (164 ft) per second. This product (150) of diameter x velocity is larger than any hitherto obtained. The Zeppelin tunnel is distinguished by the magnitude of its diameter, that of most other wind tunnels being only 2 to 2.2 meters (6.6 to 7.2 feet).

General Arrangement.— Where the greatest possible economy of construction is one of the foremost considerations, the air is drawn directly from the outside atmosphere and allowed to flow back into it again. The experiments may then be affected by the natural wind and the artificial velocity must, therefore, be considerable. Neither are the experiments practicable in all kinds of weather. In such plants, the power requirements are relatively large, since the energy still remaining in the outflowing air is lost. Behind the propeller, moreover, atmospheric pressure reigns, because this space is open to the air. In front of the propeller, i. e. in the experiment chamber, there is a corresponding negative pressure, though not exceeding 25 cm (9.8 in.) water column. Nevertheless, the air pressure variations, due to changes in velocity, are disagreeable to the experimenter. The experiment chamber must be made air-tight with reference to the external atmosphere and, during an experiment, entrance is possible only through air locks. This arrangement is designated as an "Eiffel chamber." It may be installed in a large hall, instead of in the open air, in which case disturbances due to the natural wind are

eliminated. This arrangement has the advantage that the pressure is exerted principally on the comparatively small chamber walls, thus leaving the walls of the main building comparatively free from pressure. However, in such cases there would probably be a saving in the cost of the plant, only when the hall is already built and cannot be used for other purposes.

An "Eiffel chamber" in a hall is practically a wind tunnel with a closed air circuit, since the same air is used over and over. A real air circuit is obtained by making such arrangements as save the most possible of the energy of the air. As much as 30 to 60% has thus been saved. At the same time, there is a saving in the cost of the whole laboratory, including the power plant. An especial advantage lies moreover in the fact that, through suitable ventilation, the region of changeable pressure is brought into the return circuit. Here, then, there is excess pressure. In the experiment chamber, and especially in a separate observation room, there is the pressure of the external atmosphere. It is, therefore, possible to open a window or door and to pass in or out during an experiment, without causing fluctuations in pressure.

In England and America, the second arrangement is chiefly employed, in which the observer remains in the return circuit outside the "Eiffel chamber." In Germany, the third arrangement has been especially developed and this is the one employed in the plant under consideration.

A distinction must also be made between an open and a closed air stream. The portion of the air stream utilized in the exper-

iment chamber may be confined between rigid walls or it may be allowed to flow like a jet of water through quiet air, whereby the boundary between the moving and quiet air gradually becomes less distinct toward the rear. Both arrangements have their advantages. In general, it may be said that the definitely bounded experiment chamber is the cheaper, but the unconfined air stream is the better. This depends largely, however, on the nature of the experiments. If the air stream is not inclosed, there must be quiet layers of air between the stream and the nearest walls, since otherwise there is the danger that the air stream will adhere to one wall and lose its uniformity. Hence, with an unconfined air stream, the whole arrangement is spread out too much and the balances are far from the model and are correspondingly bulky and heavy. With such an arrangement, the observer is also farther from the model and the work is correspondingly troublesome, because the model, suspended high in the air, is difficultly accessible. Lastly, the drawing together again of the spreading air stream is attended by a considerable loss of energy. This arrangement, however, has the advantage that the model may be made larger or, in other words, that the air stream corresponds, from the experimental viewpoint, to a closed wind tunnel of larger diameter. Moreover, measurements of drag are more accurate in an unconfined air stream, because it is easier to obtain a more uniform static pressure. In a closed tunnel, on the contrary, the pressure in the direction of the flow decreases or increases readily, thus making it difficult to determine accurately the drag of

long models. Since the Zeppelin plant was designed for determining among other things, the resistance or drag of airship models, the unconfined air stream was chosen.

Entrance Cone. - The cross-section of the entrance cone is a regular octagon. This shape approaches that of a circle and is more easily constructed and joined to the square tunnel. Its flat boundaries are also advantageous in many experiments. For closed experiment chambers, a square cross-section (perhaps with slightly cut-off corners) is preferable, because one can walk about and approach the walls, the same as in an ordinary room. The doors and windows can also be more readily installed. It is also advantageous to have the top of the chamber level, so as to be able to walk on it. A rectangular or otherwise oblong cross-section is not to be recommended, though it might seem, at first thought, better adapted for experimenting with long models, such as airplane wings, placed at right angles to the air stream. In this very case, what takes place above and below a wing is of especial importance and it seems better to make the cross-section of the air stream compact (i.e. about as high as it is broad).

The entrance cone in the Zeppelin wind tunnel is made of cement. It was designed with special reference to experiments with wing models, since in such experiments small changes in the direction of the air stream might completely vitiate the results. A rigid cement cone seemed to offer the best guaranty against changes in position and shape.

In the Zeppelin plant, there is a transverse passage-way under



the entrance cone, through which one may pass from one side of the air stream to the other. There was need of this innovation, since with the tunnel in operation, it would otherwise be possible to pass from one side to the other only through the air stream. This way is often obstructed by apparatus and, especially in cold weather, it requires considerable courage to pass through a wind of 50 meters (164 ft) per second. In such a wind it is not easy to preserve one's equilibrium. The lowest part of the passage, about one meter below the floor of the room, is continued in the direction of the air stream, with overhead doors. This recess receives such parts of the apparatus, underneath the experiment object, as need to be protected from the wind, especially weights for loading the model. These can be conveniently observed from the passage-way.

Exit cone.— The exit cone is made of wood, since a slight distortion or change in position does not matter. For structural reasons, its cross-section is made round, as also for adapting it to the necessarily circular opening for the propeller. The whole exit cone consists of boards running in the direction of the air stream and held in position by strong wooden hoops. The smallest inside diameter of this cone is 3.7 m (12' 1.7"), so that its smallest cross-sectional area is considerably greater than that of the outer end of the entrance cone, which is about 7 square meters. This is necessary, because the outer layer of the unconfined air stream mingles with the adjacent layer of quiet air. The mean velocity of the air stream gradually diminishes, as the distance from the entrance cone increases. The cross-sectional area of the air

stream increases correspondingly and consequently the exit cone must be larger than the entrance cone. Otherwise, the entering stream would be constricted, its marginal layers would be bent and its pressure would not be uniform. The surrounding air carried along by the air stream must, of course, flow back in some way or other. As a matter of fact, there is formed, at the entrance of the exit cone, a layer of air flowing in an opposite direction to that of the air stream and creating a draft throughout the whole room.

No very harmful effect on the experiment is thereby produced. For increasing the efficiency of the air stream, however, there are four rows of holes just behind the trumpet-shaped entrance to the exit cone. The retrograde air flows through these lateral openings and causes less disturbance. The mouthpiece is thus left entirely free to receive the inflowing air. This device also diminishes the tendency of the airflow to set up organ-pipe vibrations.

The diameter of the exit cone increases up to that of the propeller, nearly 5 meters (16.4 feet). By this expansion, a considerable portion of the kinetic energy is regained in the form of pressure and utilized in the next circulation of the air. For this purpose, the exit cone must not expand too rapidly. In expanding from a diameter of 3 m. (9.84 ft) to one of 5 m. (16.4 ft), a total length of 15 m. (49.21 ft), including mouthpiece, appears, however, to be amply sufficient.

Propeller. - This is similar to the ones used on airplanes,

and has four blades. Its diameter is 4.75 m. (15.6 ft), the mean width of each blade 50 cm (19.7 in.) and the pitch at the outer end of the blades 3 m. (9.84 ft). The maximum revolution speed is 550 RPM and the absorbed HP about 420. With such propeller blades, there is the danger that a rather strong disturbance of the air will occur, especially when the air stream is obstructed, as is often done in order to obtain a very low velocity, or from an exceptionally large resistance of a model. This disadvantage can be overcome by making the propeller blades so that their outward loading will decrease gradually. With large air streams and low pressures, such propellers have stood well and attained a high efficiency.

Return Flow.- Behind the propeller and again just before the honeycomb, the air stream is forced to change its direction. This could be accomplished most perfectly by means of a set of curved streamlined deflectors, most suitably made of cement in the case under consideration. They would accordingly stand 5 meters (16.4 ft) high, near together, and completely close the tunnel to the passage of persons. In order to avoid this and the necessity of making a number of doors, as well as the great cost of such a system, the latter was dispensed with in the Zeppelin tunnel and only suitably curved passages were employed. This omission did not result in oscillations and vibrations, nor other irregularities in the air stream. Hence any such system of deflectors may well be dispensed with in wind tunnels for technical experiments.

The Zeppelin tunnel has a divided return flow, i.e. two re-

turn conduits, one on either side of the experiment chamber. This arrangement combines symmetry of form of the ground plan, easy accessibility of the power plant and shortness of the propeller driving shaft. The bending of the air stream by the walls of the conduits is facilitated by their being only half as wide. The long conduits eliminate, by their resistance, any large oscillations of the air stream. This division of the return flow results, however, in difficult accessibility to the tunnel and experiment chamber and increases the construction cost, since a larger ground area and more walls are required.

The combined cross-sections of both return conduits amounts to 25 square meters (about 269 sq.ft), each conduit having a rectangular cross-section  $5 \times 2.5$  meters ( $16.4 \times 8.2$  ft). The cross-sectional area of the entrance cone is 7 sq.m. (75 sq.ft). The return flow velocity is accordingly almost one-third of the velocity in the experiment chamber and hence the energy required for the return flow comes into consideration. Another disadvantage resides in the fact that the air flowing right and left along the outer walls of the conduits is more or less retarded by friction and that, therefore, right in the middle of the air stream, where the model is located, irregularities of the airflow may result, which would affect the accuracy of the measurements. These irregularities have been found, however, to be very small, so that they may be disregarded.

Honeycomb. - Before the air stream enters the base of the entrance cone where, as a result of the large cross-section, it has

its minimum velocity and where the differences in velocity, arising during the return flow, are partially equalized as pressure differences, it has to pass through the honeycomb. This is a sort of sieve, made of sheet metal strips 0.5 mm (0.02 in.) thick and put together something like an automobile radiator, so as to form many small hexagonal channels. The length of these channels (i.e. the thickness of the honeycomb) is 25 cm (9.84 in.) and the mean diameter of each channel is about 3 cm (1.18 in.). Velocity differences are only slightly eliminated by the honeycomb, its function being rather to eliminate cross currents in the air stream. The air stream has a spiral motion, given to it by the propeller, which must be eliminated as much as possible. Before entering the honeycomb, in the plant under consideration, this spiral motion is especially pronounced, due to the absence of the deflectors already referred to and the comparatively low revolution speed of the propeller. The resistance offered by the honeycomb raises the power requirement several HP. This loss, however, is somewhat offset by a lessening in the tendency to set up oscillations in the whole air stream.

Balances.- In other countries, it is customary to secure the model to a rigid rod, the other end of which is held by a complicated mechanism for measuring the various force components. In Germany it is preferred to suspend the model by means of small wires, at least six such wires being required for holding the model rigid. Then either the pull on each wire is measured directly or two or more wires are connected with the same balance.

The advantage of the German method resides first in the fact that the results are much less affected by the small wires than by a rod. Moreover, the whole system is composed of a number of simple balances, either one of which can be used alone. Consequently such a balance is more reliable and accurate than any unusual and complicated system of balances. The balances must leave it possible to change the angle of attack of the model during the experiment, without rehangng. This is accomplished in the Zeppelin plant in a particular way. Both balances, to which the model is attached, can be raised or lowered. In the room over the experiment chamber, a strong frame of U-iron is built into the floor for supporting the balances. Each balance (Fig. 3) consists of a post with two vertical guide-rods about 1.2 m. (3.94 ft) apart. On these guide-rods there slides a support for the balance. This support can be raised or lowered by winding up or unwinding two wire cables. The balances themselves are beam balances and differ from ordinary beam balances only in their great width of beam. Each balance rests on a pair of self-adjusting knife-edges perfectly alined with each other, on either end of the movable support. The beam, to which the cables are attached, is almost 3 m. (9.84 ft) long and likewise rests on a pair of knife-edges. All the knife-edge supports are self-adjusting, the same as on platform scales. Two such balances are pushed so near together that the distance between the suspension points is exactly the same as the distance between the suspension points of the model. The balances are also raised until their connecting line is parallel to the line connecting the sus-

pension points of the model. Thus a parallelogram is formed by the suspension wires, the line connecting the suspension points and the supporting beams. The problem is now to preserve this parallelogram, while changing the angle of attack. This is accomplished in the Zeppelin laboratory by having only one balance clamped fast during the experiment, while the other balance glides on rollers along its support and is held by two rods which connect the supporting tables of both balances. If the second balance is now raised or lowered, the direction of these connecting rods is changed and the second balance is, at the same time, moved a short distance horizontally. Although the balance-beam table is thus moved vertically with respect to the balance stand, it moves in an arc with respect to the first balance, since it is held at a fixed distance from the latter by the two guide rods. The angle between the connecting rods of the balance and the horizontal may be read, thus obtaining directly the change in the angle of attack. For determining the drag and, if required, other components of the air forces, four other small balances are provided. These are, in principle, only ordinary beam balances made especially strong for this purpose.

The balance for measuring the drag exhibits one peculiarity. From the model a wire runs horizontally against the wind. It then forms a fork with a wire running downward at an angle of 45 degrees (fastened at its lower end) and a vertical wire attached to one end of the balance beam. By this device, increased stability is obtained with respect to the balance, i.e. when the balance pointer swings, the transmission from the model to the balance

will be changed on account of the change of angle at the junction of the three wires in such manner that the sensitiveness of the balance is diminished according to the loading of the balance. Consequently, the reading of the drag balance is less accurate. This is a disadvantage, since the resistance or drag to be measured is often very small and is only obtained as the difference of relatively much larger readings. In order to eliminate this disadvantage, however, the balance itself was so constructed that, without the wire suspension, it would become more sensitive with increasing load. By the joint action of the suspension and the specially constructed balance, a balance arrangement is obtained with unchangeable sensitiveness. This result is obtained by placing the middle knife-edge of the balance, not, as customary, on the line connecting the other two knife edges, but somewhat lower.

Disk weights of 10 kg (22 lb), 1 kg (2.2 lb), and 100 g (.22 lb) are used, the last 100 grams being measured by a sliding weight, which is moved one millimeter for every gram. The lift balances, from which the model is suspended, allow a loading of only 200 kg (441 lb) each. The balances are accurate to within one per cent. Readings may be made down to one gram and with care even to one-fifth of a gram.

Suspension Frame.- On account of the large dimensions of the Zeppelin wind tunnel a special frame is required for installing the model. It would be very inconvenient to depend on any combination of oscillating frames. From the ceiling of the experiment chamber there hang at a suitable height, each on four parallel rods,



two adjacent rectangular platforms capable of being walked on and of being withdrawn from the air stream to either side by means of a rope and windlass. The outer suspension rods are fastened together to form a rigid frame. The adjacent platforms are coupled together. When all four lateral ropes (joined in pairs and each pair served by one windlass) are drawn taut, the hanging platforms are almost as rigid as a solidly built floor, rendering it perfectly convenient to install and adjust the model. The platforms always remain horizontal and may be walked on in any position.

Power Plant.- The propeller is driven by two 220 HP gasoline engines which make about 1400 RPM. The power is transmitted by means of reduction gears, to the propeller shaft, which makes up to 550 RPM. Either engine may be cut out separately and it is also possible to start one engine by means of the other. The same driving gear is employed as in the twin-engine cars of the Zeppelin airships. It is often considered better to equip wind tunnels with electric motors, since the latter run more smoothly and can be regulated better. It must, however, be considered that there are very few electric power plants large enough to enable a sudden switching on and off of 400 HP, as is constantly necessary in the operation of a wind tunnel. Often the engine in the electric plant is not enough larger than the driven motor to prevent strong oscillations of the voltage and corresponding difficulties of adjustment. This adjustment can be accomplished in such large electric motors only by means of a Leonard generating set, which is disproportionately expensive.

Regulation of the Power Plant. - In performing the experiments, it is not only necessary to have a uniform velocity in all parts of the experiment chamber but also during the whole experiment. The latter is, in fact, more important than the former. In the Zeppelin laboratory, a special regulator is employed whose function is to preserve uniformity and prevent oscillations of the engine or air stream. For this purpose, the throttles of both engines are connected by a rod with a float, which is raised or lowered by the inflow or outflow of the liquid in the float chamber. This in and out flow is regulated by an electromagnet, which is switched on or off by the swinging of a small balance. The latter is a beam balance which rests on a knife-edge and on which rest two other knife-edges for supporting the suspensions. From one of the knife-edges there hangs a beaker with mouth downward and dipping in a liquid (Fig. 4). It is filled with air which communicates with the entrance cone by means of a tube entering the beaker from below. This knife-edge also supports a scale-pan for receiving weights. The whole mechanism is a device for determining the pressure in the entrance cone. When this pressure just equals the weights on the pan, the balance beam remains horizontal and the float and throttle remain undisturbed. According to whether the pressure increases or diminishes, the balance swings one way or the other and allows, e.g., the water to flow out of the float chamber, thus shifting the throttle until the pressure in the entrance cone corresponds to the weights on the scale-pan. This device is not only adapted for maintaining a uniform pressure

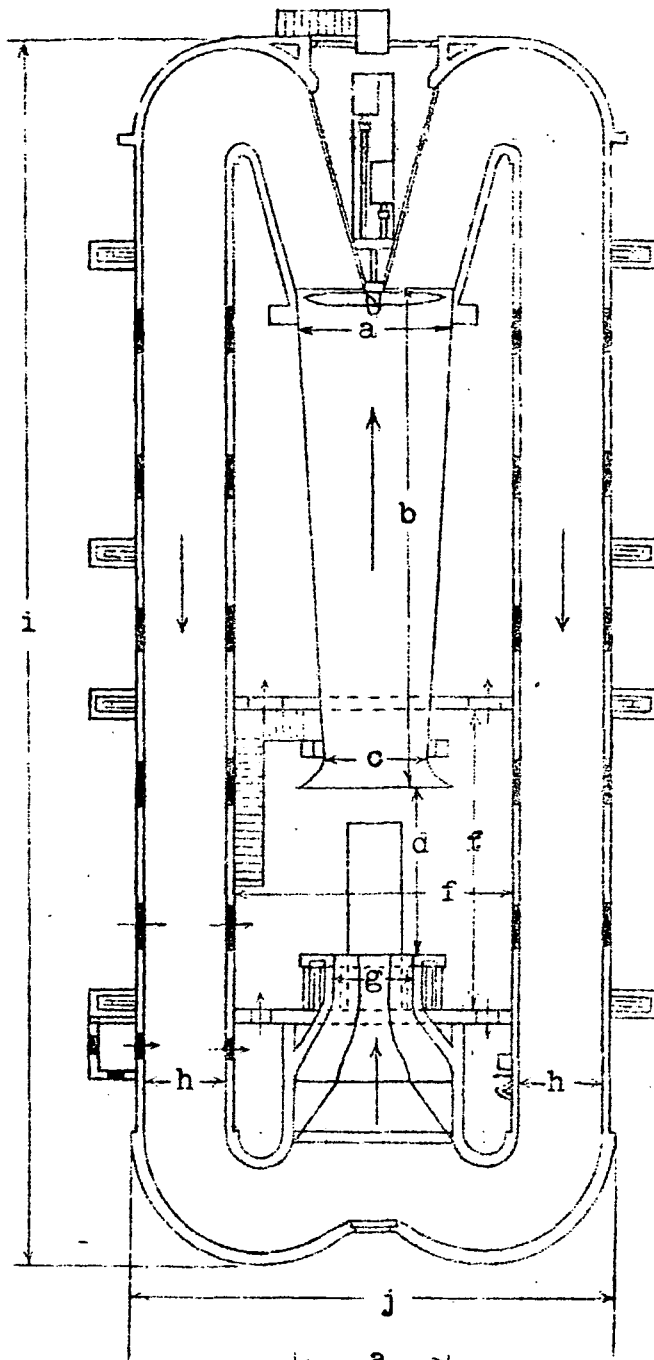
in the entrance cone and hence in the experiment chamber, but may also be employed for varying the RPM of the engine, and consequently the velocity of the air stream, from the observation room, without intervention on the part of the engineer. It is only necessary to vary the load on the pressure-regulating balance in the observation room above. A certain length of time must elapse, however, from the instant when, as a consequence of the changed pressure in the entrance cone, the regulating balance begins to move the throttle, before the changing pressure in the entrance cone makes itself felt. Consequently, this device would tend to over-regulate and the engine would be affected more than is necessary. Then the pressure-regulating balance would again produce the opposite effect and also to a greater degree than necessary, so that, instead of a uniform velocity of the air stream, a constantly oscillating velocity would result. In order to minimize these oscillations, a second knife-edge supports another inverted beaker hanging in a liquid. This beaker is connected with a chamber which, in turn, is connected with the above-mentioned float chamber, but is otherwise completely closed. When the float rises, the water also rises in the other chamber, the displaced air passing up into the return beaker of the regulating balance and thus bringing the regulating process to a sufficiently early conclusion. The return beaker is connected with the outside air by a small opening through which the pressure is gradually equalized.

Results Obtained. - It has already been mentioned that the maximum velocity of the air stream is about 50 m. (164 ft) per

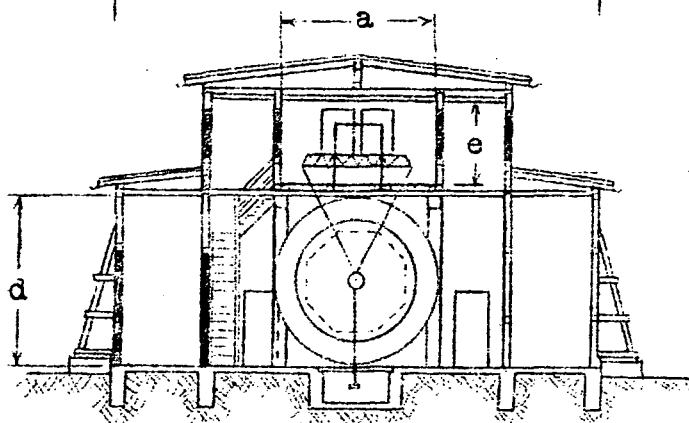
second, the minimum velocity being about one-third as much, 16 m. (52.5 ft) per second. The velocity is very nearly uniform throughout the whole cross-section, it being possible to determine variations only with the greatest pains. The uniformity with time is not quite so satisfactory, since the above-described method of regulating serves only to keep the mean value constant over a longer period of time, but fails to eliminate the smaller periodic oscillations in velocity. These oscillations amount, however, to only about 2% and do not materially affect the results....

The above-described wind tunnel is a compromise between different designs. The original design was made by P. Jaray. From his design there have been retained the dimensions of the building, the location and arrangement of the engine room, the construction of the propeller and the two return conduits. The remaining details, as likewise the general plan, were left to the writer. In the final installation of all the apparatus, he was efficiently assisted by the engineer, Paul Schönfeld, who thus contributed materially to the successful completion of the plant.

Translated by  
National Advisory Committee  
for Aeronautics.



- a- 15.75 ft.
- b- 49.21 ft.
- c- 12.14 ft.
- d- 16.40 ft.
- e- 8.53 ft.
- f- 28.87 ft.
- g- 9.51 ft.
- h- 8.04 ft.
- i- 119.75 ft.
- j- 47.57 ft.



Figs. 1 & 2

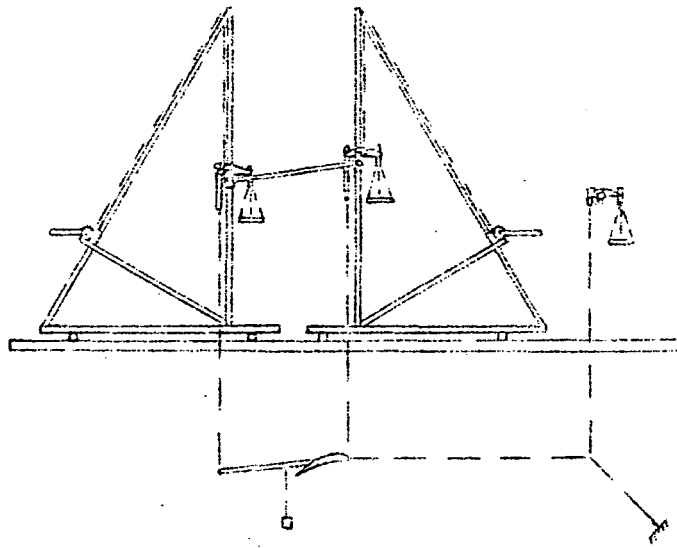


Fig. 3.

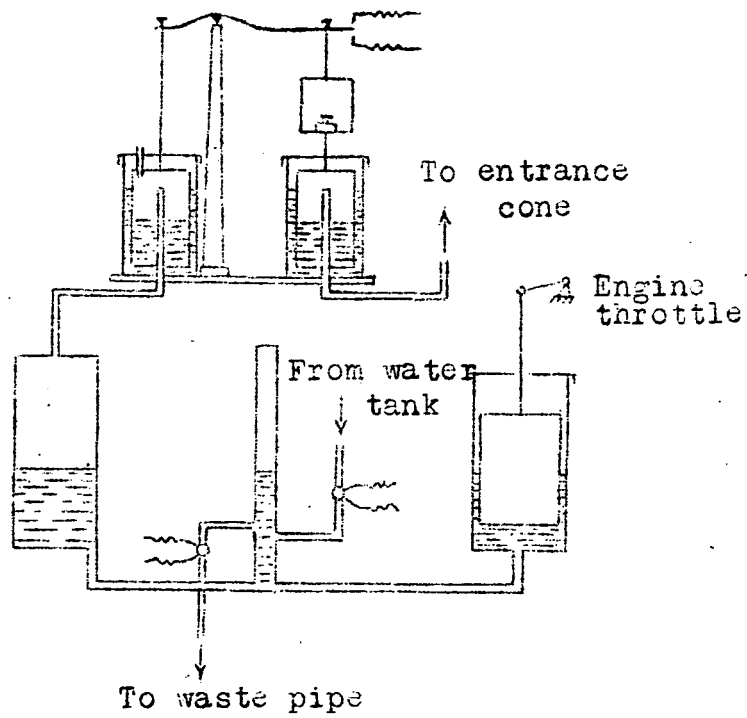


Fig. 4.